INVESTIGATION OF OXYGEN INJECTION USING SMALL-BUBBLE DIFFUSERS AT FORT PATRICK HENRY DAM

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Fort Patrick Henry Dam is located on the South Fork Holston River at river mile 8.2, about 2.5 miles upstream from Kingsport, Tennessee, and 10.4 river miles downstream from Boone Dam (Fig. 1). At normal maximum pool (elevation 1,263), the reservoir extends 10.3 miles upstream and has a total volume of 27,100 acre-feet. The reservoir has 4,300 acre-feet of useful control storage between normal maximum pool level and normal minimum pool level (elevation 1,258). The maximum depth of the pool immediately upstream from the dam is approximately 70 feet. Average streamflow at Kingsport was 2,522 cfs during the period 1925-1970. The dam is equipped with two hydraulic turbines, each of which has a generating capacity of 18,000 KW. Normal maximum discharge through each turbine is 4,400 cfs.

The dissolved oxygen (DO) concentration in the turbine releases from Fort Patrick Henry Dam are less than 5 or 6 mg/ℓ for about six months each year during the summer and fall months. Based on a 20-year monitoring program, the minimum concentration is usually about 2 mg/ℓ, although occasionally the minimum approaches 0.5 mg/ℓ. Fig. 2 summarizes the DO in the turbine discharges from Fort Patrick Henry for the period 1960-1972.

The dissolved oxygen problem at Fort Patrick Henry Dam is the combined result of 1) the inflow water from Boone Dam having a low DO and 2) additional depletion of oxygen in the hypolimnion of the stratified Fort Patrick Henry

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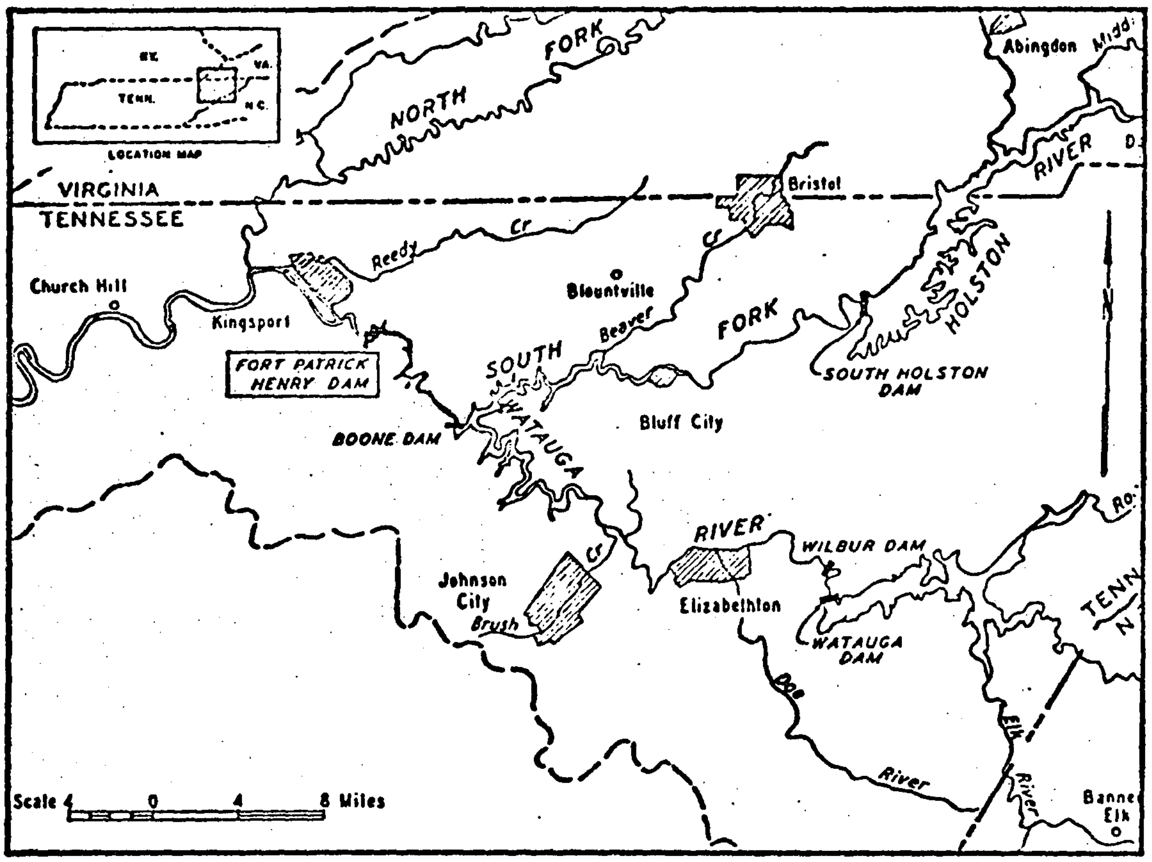

FIG. 1.--Map of Fort Patrick Henry Dam Project Area

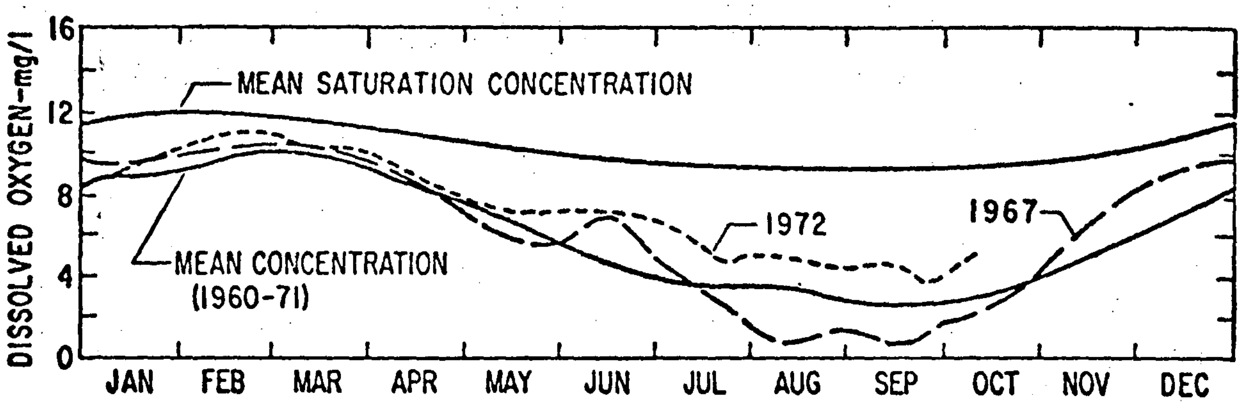

FIG. 2.--Dissolved Oxygen Conditions in the Turbine Discharge from Fort Patrick Henry Dam

Reservoir. During periods of maximum turbine discharge and minimum DO, it is estimated that 8 miles of free-flowing stream below the dam would be required for reaeration to about 5 mg/ℓ. This low DO level affects a reach of stream immediately below the dam that has been classified as a trout stream by the State of Tennessee and also compounds a water pollution problem that exists downstream from Kingsport.

In 1971 a study was initiated to develop a system for reaerating the turbine releases to a more desirable DO level. This paper discusses some of the considerations in selecting the oxygenation system, describes the project that ensued, and presents some of the recent results.

SELECTION OF AN AERATION SYSTEM FOR INVESTIGATION

Methods of correcting low DO problems in reservoir releases may be broadly classified into three major groups: (1) control of DO concentrations within the reservoir, (2) selective withdrawal of reservoir water with acceptable quality, and (3) aeration of reservoir releases (2). To systematically consider the various methods available, a matrix was constructed to compare the various available methods against the conditions under which the methods would have to be applied for Fort Patrick Henry (Table 1).

Reservoir aeration was considered infeasible at Fort Patrick Henry Dam. The stream reach below the dam is classified as a cold water fishery and destratification would increase water temperatures in the releases. In addition, there was concern that aeration of the hypolimnion with air would introduce a problem of nitrogen supersaturation. Aeration of the hypolimnion with oxygen might be feasible, but was considered unattractive because of reservoir hydraulics and capital cost.

The volume of water in the well-aerated epilimnion and the probable rate of replenishment of this volume were too limited to allow selective

TABLE 1.--Applicability of Various Aeration Methods for Fort Patrick Henry Dam

Conditions Under Which Applicable Aeration Technique is to be Applied	Group I Reservoir Aeration		Group II Selective Withdrawal		Group III Aeration of Reservoir Releases						
	Destratification 1. Mechanical Pumping 2. Diffused Air	Hypolimnion Aeration 1. Diffused Air 2. Diffused Oxygen	Submerged Weir 1. Inflexible 2. Flexible	Multi-Level Intakes	Turbine Venting	U-Tube Aeration 1. Compressed Air 2. Oxygen Gas	Mechanical Aerators	Weir Aeration	Side-Stream Supersaturation	Oxygen Injection Upstream 1. Penstock 2. Diffuser 3. Downflow Bubble Contact	Tailwater Diffusers 1. Oxygen 2. Compressed Air
Coldwater tailwater	- -	+ +	- -	-	?	+ +	+	+	+	+ + +	+ ?
Tailrace deeper than 10'					+				+		+ +
High DO increase	- -	? ?	+ +	+	-	+ +	?	+	+	+ + +	+ ?
Fluctuating reservoir pool			- +								
Minimal effect on power production	+ +	+ +	+ +	+	?	- -	-	-	-	? + +	+ -
Minimal increase in dissolved nitrogen	? ?	- +	+ +	+	?	- +	+	?	+	+ + +	+ ?
Low Capital Cost	+ +	- -	- -	-	+	- -	-	-	-	+ + +	+ -

Note: + indicates a relatively positive effect of the particular aeration method.
- indicates a relatively adverse effect of the particular aeration method.
? indicates an unknown effect on the condition indicated.

withdrawal of water with a high concentration of DO. Even if selective withdrawal were possible, capital cost would be high and increased water temperatures downstream would result.

Thus, for the installation at Fort Patrick Henry Dam, methods of reaerating releases were considered most feasible. A review of the possible methods indicated that turbine venting would not increase DO concentrations to desired levels. U-tube aeration was determined to be uneconomical because of high capital cost and reduced efficiency of power generation resulting from loss of head on the turbines. In addition, nitrogen supersaturation was a concern. Weir aeration was also determined uneconomical because of high capital cost (approximately $2,000,000) and reduced efficiency of power generation. Mechanical surface aerators were uneconomical because of the large number (about 90) of units required. For Fort Patrick Henry Dam, it appeared that diffused air aeration in the tailrace and injection of molecular oxygen into the turbine releases were most feasible.

Disadvantages of diffused air aeration as compared to oxygen injection were (1) a high power requirement for air compressors (about 5 percent of the power generating capacity of the plant), (2) a lower capability for adding DO at concentrations greater than about 5 mg/ℓ, and (3) a higher capital cost. Estimates from data on diffused air aeration for sewage treatment plants (1) indicated that an installation at Fort Patrick Henry Dam for aeration to 5 mg/ℓ would require at least 3,000 horsepower to drive the needed air compressors and 15,000 fine-pore diffusers such as those used in sewage treatment plants. The diffusers in the tailrace would cover an area about 100 feet wide and over 250 feet long. The estimated total annual cost for diffused air aeration was about $180,000 for aeration to 5 mg/ℓ and $220,000 for aeration to 6 mg/ℓ (1972 dollars).

The advantages of oxygen injection are that high DO levels can be obtained, the initial investment is relatively low for some of the techniques, and the effects on peaking power production should be negligible for most methods. Of the various techniques of injecting oxygen into turbine releases, diffuser injection either upstream or downstream from the dam appeared most feasible. The main disadvantage of using pure oxygen was the high cost of oxygen. However, even with this high operational cost, this method was estimated to compare favorably with and possibly be even less costly than diffused air aeration (2).

The side-stream supersaturation system did not appear economical because in addition to the oxygen required, the horsepower required to pressurize the side-stream was estimated to be comparable to that required for diffused air aeration.

The downflow bubble contact system proposed by Speece (4) may have been feasible; but, because of the relatively shallow reservoir depth, a large portion of the turbine release would have to pass through the bubble contact system.

The method chosen for development for use at Fort Patrick Henry was diffused oxygen upstream from the turbine intakes. Upstream injection was selected for the following reasons:

1. The longer contact time between the reservoir water and the gas bubbles improves transfer efficiency.

2. The allowable mass flux rate of oxygen through the diffusers is directly proportional to the depth of water. This means that the size of the diffuser system can be reduced for greater depths of water.

3. Transfer efficiency increases proportionally with depth because the partial pressure of oxygen in a bubble increases with depth while that for dissolved nitrogen generally remains the same at all depths. Transfer efficiency is proportional to the ratio of the partial pressure of oxygen in bubbles to that of dissolved nitrogen in the water.

It was recognized that upstream injection may have several disadvantages if all the oxygen was not absorbed and bubbles were allowed to pass through the turbine system. Possible problems include a reduction in turbine efficiency, corrosion of the turbine and the associated discharge system, and adverse effects on pressure taps used to measure turbine discharge. It was also recognized that downstream injection would not affect the turbine discharge system and that it is conceivable that the turbulence downstream from the dam could effect a high oxygen transfer efficiency. However, the investigators concluded that upstream injection appeared to be more promising.

It was also concluded that a liquid oxygen storage tank probably would be the source of oxygen gas, as opposed to on-site generation, because the oxygen requirement is seasonal, highly variable, and relatively low (3). The monthly demand for oxygen during an average year ranges from about 25,000 pounds to 1.1 million pounds. Oxygen would normally be required only six months of each year. The annual oxygen requirement ranged from 3.5 to 6.3 million pounds per year to achieve a DO concentration of 6 mg/ℓ and from 1.7 to 4.1 million pounds per year to obtain a concentration of 5 mg/ℓ (Table 2).

SELECTION OF A DIFFUSER FOR FIELD TESTING

Since oxygen injection by means of diffusers had not been investigated, research was necessary to determine the feasibility of such a scheme. The investigation for Fort Patrick Henry Dam was conducted in two phases to determine first the best diffuser for injecting the oxygen and second the best location for injecting the oxygen.

The best diffuser system would be one that provided the greatest oxygen absorption, required the smallest number of diffuser units, and entailed

TABLE 2.--Annual Oxygen Requirements for Turbine Discharges from Fort Patrick Henry Dam - 1960-1974

Year	Oxygen Required to Provide the Following Minimum Downstream Dissolved Oxygen Concentrations, lbs/yr	
	5 mg/ℓ	6 mg/ℓ
	$x\ 10^6$	$x\ 10^6$
1960	3.51	5.73
1961	2.26	4.50
1962	3.20	5.15
1963	4.07 (max.)	6.30 (max.)
1964	3.13	5.33
1965	2.32	3.86
1966	3.68	5.58
1967	2.64	4.05
1968	1.71 (min.)	3.55 (min.)
1969	2.57	4.25
1970	2.42	4.46
1971	1.90	3.65
Average	2.78	4.70

fewer problems of maintenance and installation. The first phase of the study was designed to determine (1) possible maintenance problems and solutions to these problems and (2) oxygen absorption efficiencies for several available diffusers using laboratory studies.

Diffusers can be plugged or clogged by one or more of the following: (1) sedimentation of silt and other solid material on the diffusers, especially when oxygen is not being injected, (2) biological growths on the diffusers, (3) precipitation of chemically reduced chemical compounds in the water, which tend to plug the diffuser pores when oxidized by the oxygen, and (4) filtration occurring when water enters the diffuser system while it is dormant. These possible maintenance problems were evaluated in a small-scale field study as presented in another paper by Vigander (6).

Plugging that might be caused by oxidation of chemically reduced ions and compounds was evaluated in the laboratory. Oxygen was injected through the diffuser with the smallest pores in a tank filled with water that had a ferrous iron concentration similar to that of the reservoir during critical conditions. The diffuser did not clog after being tested intermittently 8 hours a day for about 2 months for a total of 317.5 hours (3).

To compare relative oxygen transfer efficiencies and to select a diffuser for the second phase of the study, diffusers were evaluated in a large tank at TVA's Engineering Laboratory in Norris, Tennessee. The 45-foot-deep tank was designed to simulate the depth of the hypolimnion in Fort Patrick Henry Reservoir. A 7-foot diameter was selected so that the volume of water in the tank would be sufficient to limit the rate of DO increase during testing to about 1 mg/ℓ per minute and to minimize the effects of the side wall. The results of these studies were reported by Vigander (6). These tests allowed the evaluation of the effect on oxygenation efficiency of diffuser material, pore size, diffuser attitude, bubble rise height, static pressure, and oxygen flux.

FIELD TESTS ON OXYGEN TRANSFER EFFICIENCY

On the basis of Phase I studies and taking into account the prices of the various diffusers, it was concluded that the most promising diffuser appeared to be a cintered alumina tube with a 15-20 (estimated) micrometer pore size. This diffuser thus was selected for Phase II field tests.

One hundred and thirty-six diffusers were mounted in four rows on each of ten frames as shown in Fig. 3. The frames were set about eight feet above the bottom of the reservoir. A catamaran work barge with an overhead hoist was used to service and move the diffuser frames. Three diffuser frame positions were tested as shown in Fig. 4.

During each test the following measurements were made: 1) the rate of oxygen injection through the diffusers, 2) the incremental increase in DO in the tailwater, and 3) the turbine discharge. All tests were conducted during a relatively constant discharge through unit 2; unit 1 was never in service during testing. A typical test proceeded as follows: the desired turbine discharge was set and DO was monitored at the downstream measuring station (Fig. 4) until a steady state condition had developed. Then, the preplanned oxygen injection rate was established through the diffusers and the DO again monitored at the downstream station until a steady state condition had developed. Approximately a 1-hour time lapse occurred between the time the injection rate was set and the time a steady state condition could be measured at the downstream station. When it was possible to obtain constant turbine discharges

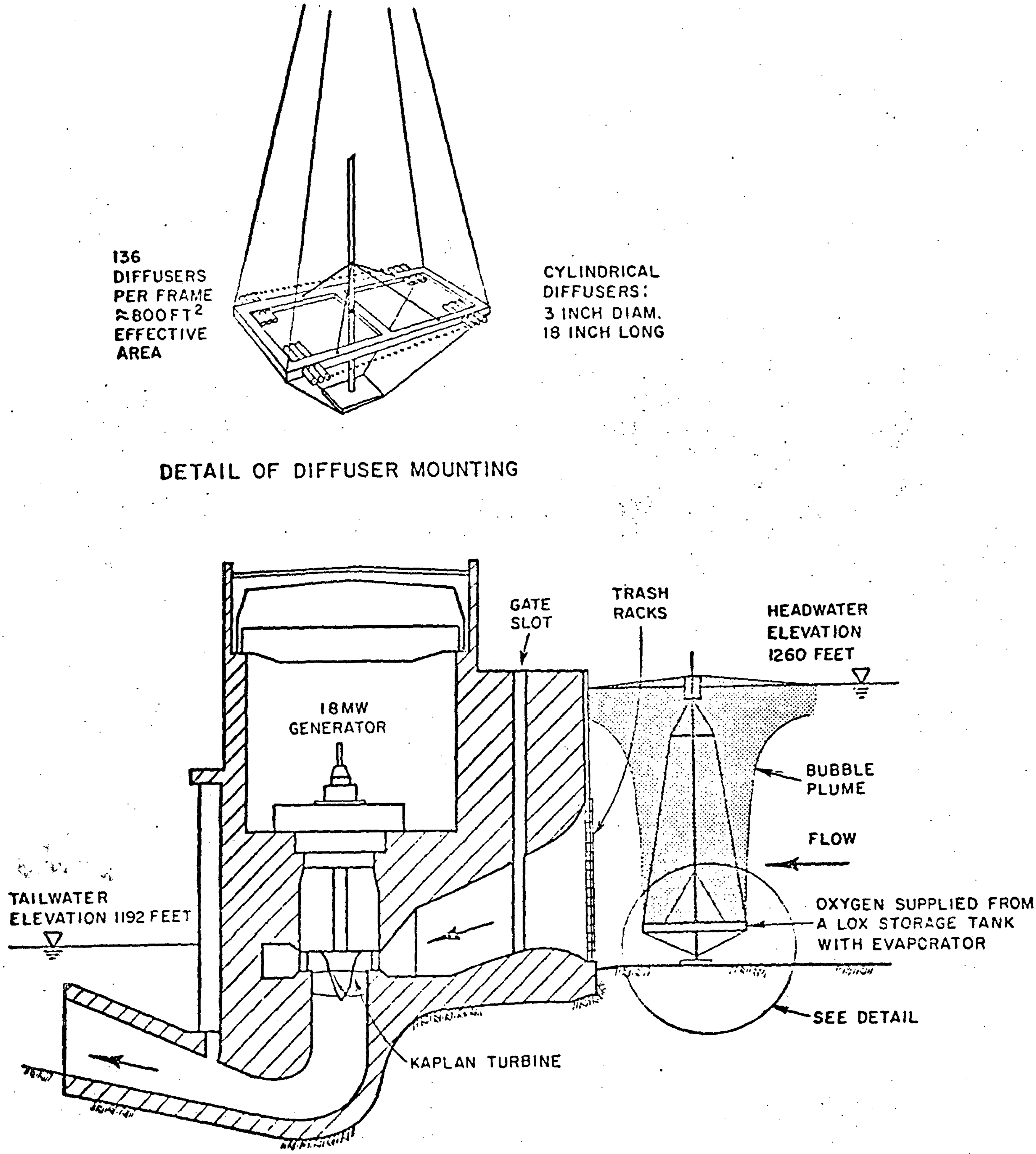

FIG. 3.--Definition Sketch for the Small-Bubble Oxygen Injection Method.

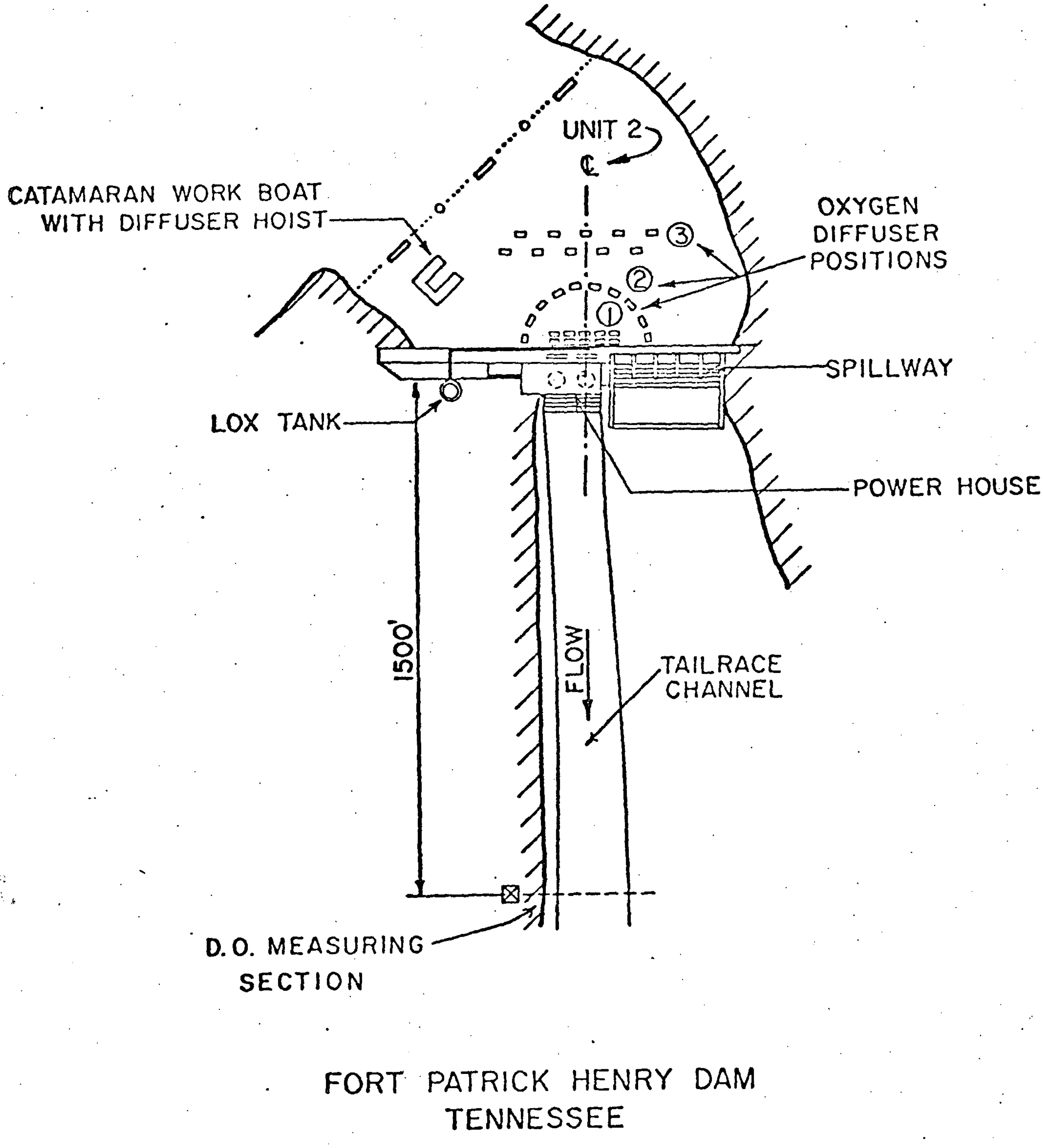

FIG. 4.--Plan View of the Oxygenation Pilot Installation. Position No. 1 was about 15 feet from the face of the dam; No. 2, about 70 feet; and No. 3, about 150 feet.

for long periods of time, several oxygen injection rates were evaluated consecutively. On several occasions during testing, the DO in the tailwater was measured across the cross-section and between the dam and downstream sampling station; no significant variation in DO was observed in either direction.

The results of the field studies using this diffuser were reported by Vigander and Ruane (5). In essence, the results obtained indicated that transfer efficiencies were not as high as those observed during laboratory studies. In the range of flux rates from .01 to .12 acfm/ft^2, the laboratory results indicated that oxygen efficiencies in the range from 80 to 100 percent should be achievable; however, in the field tests oxygen transfer efficiencies ranged from about 30 to 90 percent.

The variables evaluated in these field tests were flux, turbine discharge, and location. In all cases, transfer efficiency decreased as the flux increased. The effect of turbine discharge on transfer efficiency was significant only for location No. 1 where the diffusers were located immediately in front of the turbine intake. In this case transfer efficiency was much better for the higher discharges. Apparently at these higher discharges many of the very fine bubbles were carried through the turbine system, allowing more time for absorption. Streamflow did not affect transfer efficiency when the diffusers were 70 feet upstream from the intake; but when the diffusers were 150 feet upstream, transfer efficiency increased slightly at maximum turbine discharge. For the normal turbine discharge of 3,000 cfs, location of the diffusers was not a significant variable, particularly for transfer efficiencies greater than 60 percent; for transfer efficiencies less than 60 percent, transfer efficiency decreased significantly for the third position--150 feet upstream from the turbine intakes.

As a result of the relatively low transfer efficiencies obtained using the first diffuser, it was decided to (1) evaluate in the field the lab-tested diffuser having the smallest pore size, and (2) determine the effect of spacing between the diffusers. According to laboratory tests (Fig. 5), the smaller-pore diffuser, which is an aluminum alloy plate having pore sizes ranging between 1-1/2 and 2 micrometers, had a significantly smaller mean bubble size for the range of oxygen flux considered. In addition, the oxygenation efficiency observed in the laboratory appeared to be somewhat greater for the smaller-pore diffuser; however, since the smaller-pore diffuser was a plate and the other diffuser was a tube, it is not practical to compare transfer efficiencies on the basis of flux because the entire surface area of the tube is not used to generate bubbles. The laboratory oxygenation efficiency of the smaller-pore diffuser is shown in Fig. 6.

The smaller-pore diffusers were evaluated in the field at location No. 2. The frames illustrated in Fig. 3 were used to support a total of 520 diffusers. Each diffuser had an overall length of about 3.7 feet, a width of 3 inches, and a thickness of about 1 inch. The spacing between the diffusers was about three inches. The total active diffuser surface area was about 380 ft^2.

The results of these field tests are shown in Fig. 6. The results indicated that higher transfer efficiencies could be achieved with the smaller-pore diffuser at relatively low oxygen flux rates. Also plotted in Fig. 6 for comparison are the data for the lab tests for the smaller-pore diffuser and the data for the laboratory and field tests for the larger-pore diffuser. The figure indicates that for both diffusers the transfer efficiencies observed in the field tests were less than those observed during laboratory studies; however, the difference between lab and field transfer efficiencies was greater for the larger-pore diffuser. For the larger-pore diffuser the transfer efficiency dropped approximately 30 percent in the field as compared to the laboratory, assuming the goal was to

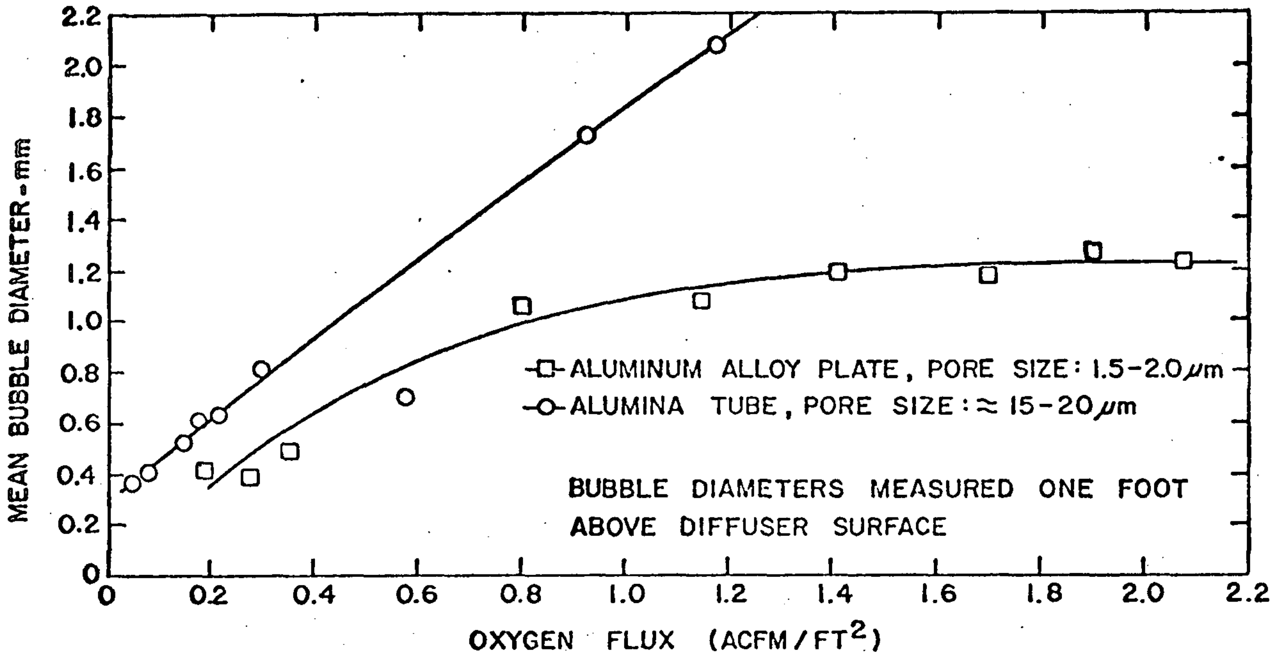

Fig. 5.--Mean Bubble Size at Various Flux Rates for the Two Diffusers Evaluated in Fort Patrick Henry Reservoir

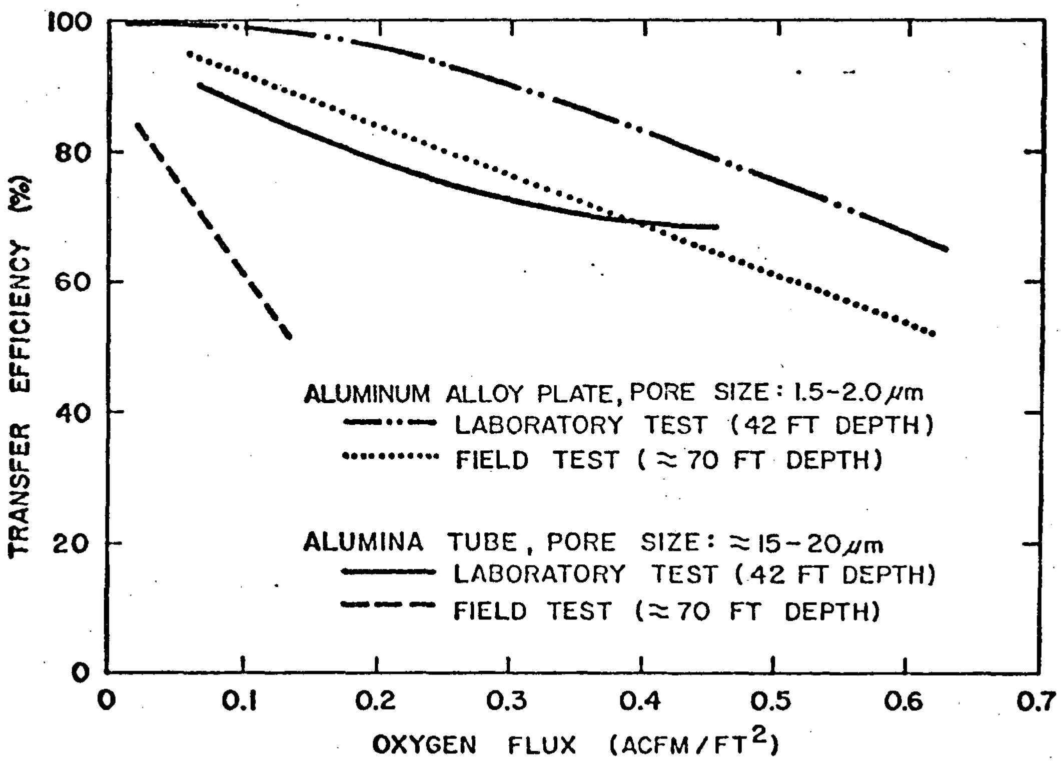

Fig. 6.--Transfer Efficiency vs. Flux Rate for Two Diffusers Evaluated Under Both Laboratory and Field Conditions

achieve 90 percent transfer efficiency based on laboratory results. For the smaller-pore diffuser the transfer efficiency decreased only about 10-15 percent, assuming a 90 percent transfer efficiency was the goal based on laboratory results. An advantage of the smaller-pore diffuser appears to be the ability to operate over a wider range of flux rates without sacrificing excessive transfer efficiency. This would allow the designer to design the oxygenation system for a more average oxygen requirement, using a higher - but slightly less efficient - oxygen flux for peak oxygen requirements. This could significantly reduce costs for the diffuser system.

Tests to determine the effect of spacing between diffusers on oxygen transfer efficiency were conducted using the larger-pore diffusers. The percent of oxygen in the off-gas (that gas which is unabsorbed and reaches the water surface) was measured during various flux rates for both the full frame of diffusers and a single diffuser. In these studies the percent oxygen in the off-gas was used as an indication of relative oxygen transfer efficiency. The results of these studies are shown in Fig. 7. Plotted in this figure is the percent oxygen in the off-gas versus oxygen flux rate for the full frame, a single diffuser in the field, and a single diffuser in the laboratory. The percent of oxygen in the off-gas during the full-frame tests was considerably higher than that for a single diffuser in the field; and, the percent of oxygen in the off-gas for a single diffuser in the field was somewhat greater than that found in the laboratory. The figure indicates that spacing between the diffusers has a significant effect on relative oxygen transfer efficiency and that percent transfer efficiency in the field is somewhat less than that obtained in the laboratory. The difference between the field and lab tests probably is a result of either a difference in water quality or side-wall effects of the tank in the laboratory. Similar studies are underway for the smaller-pore diffuser.

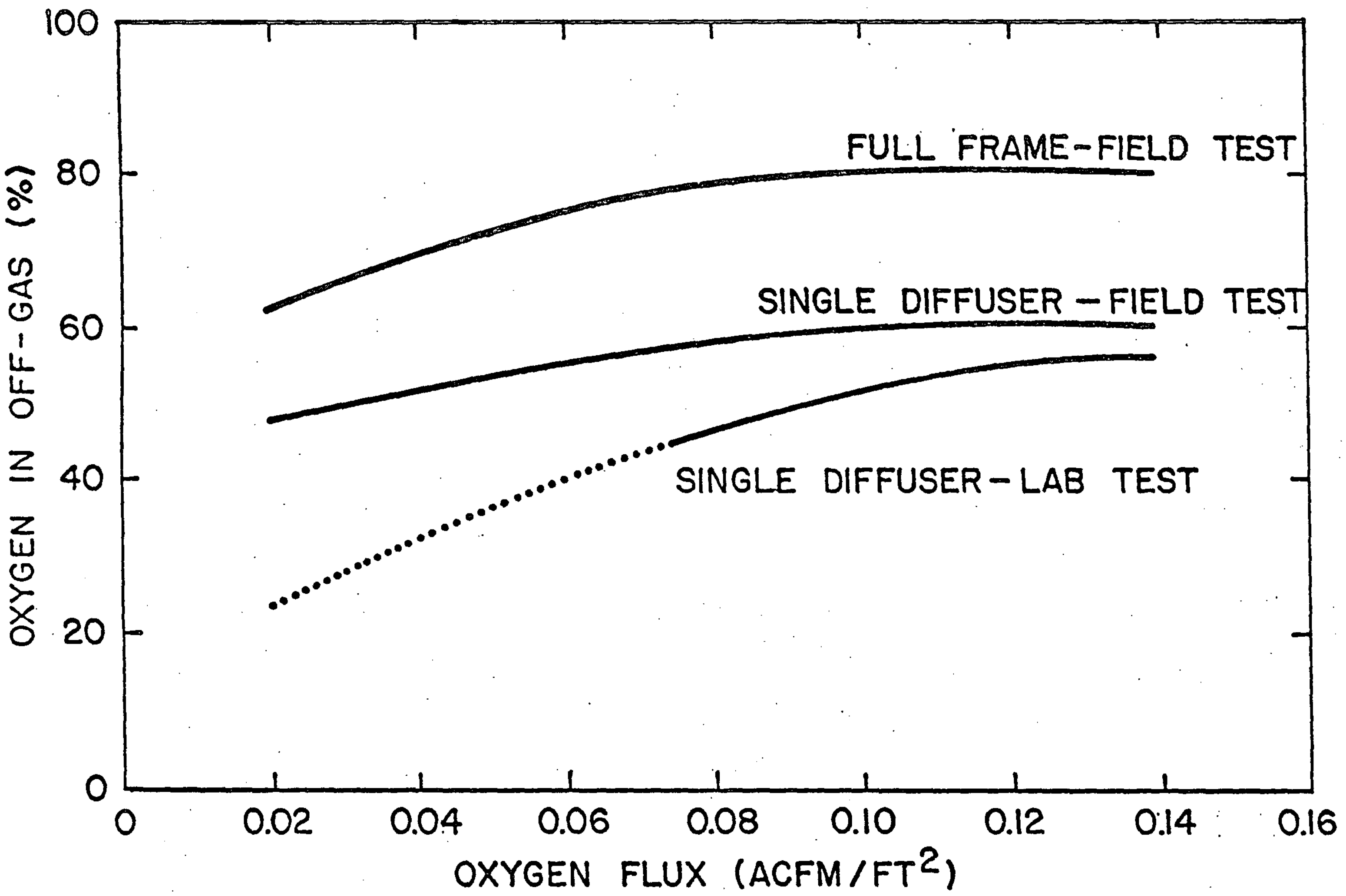

Fig. 7.--Percent Oxygen in the Off-Gas vs. Flux Rate to Show the Effect of Spacing Between the Larger-Pore Diffusers (Depth of water over the diffusers was about 40 feet.)

CONCLUDING REMARKS

1. A systematic procedure was presented for selecting promising solutions to DO problems in reservoir releases. The method selected for development for Fort Patrick Henry Dam was oxygen injection using small-bubble diffusers located upstream from the turbine intake.
2. Laboratory and small-scale field studies were conducted to select the most promising diffuser on the basis of transfer efficiency, an evaluation of operation and maintenance problems, and economics. This diffuser was then evaluated in pilot-scale testing and found to yield considerably lower transfer efficiencies than measured in the laboratory. Another diffuser having a smaller pore size was then evaluated and found to yield more promising results.
3. The effect of spacing between the diffusers was found to affect significantly the transfer efficiency of the larger-pore diffuser. The effect of spacing on the transfer efficiency of the smaller-pore diffuser is now being evaluated.
4. An economic study is now underway to determine which diffuser should be used for a full-scale system and to compare this method of oxygenation with the estimated cost of other means of aeration.
5. Since 1971 DO levels in the Fort Patrick Henry Dam discharge have increased significantly. The reason for this improved condition has not yet been determined; however, if it can be attributed to reduction in wastewater discharges upstream from the dam or possibly other controllable factors, these factors will be taken into account prior to installing a full-scale oxygenation system at the dam.

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